COSMIC STRUCTURE OF MAGNETIC FIELDS

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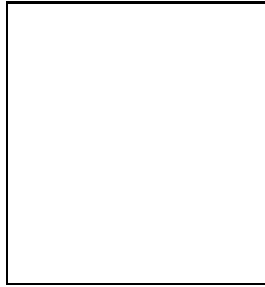[4] *Department of Astronomy & Space Science, Chungnam National University, Daejeon 305-764, Korea*
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The simulations of the formation of cosmological structure allows to determine the spatial inhomogeneity of cosmic magnetic fields. Such simulations, however, do not give an absolute number for the strength of the magnetic field due to insufficient spatial resolution. Combining these simulations with observations of the Rotation Measure to distant radio sources allows then to deduce upper limits for the strength of the magnetic field. These upper limits are of order 0.2 to 2 μgauss along the filaments and sheets of the galaxy distribution. In one case, the sheet outside the Coma cluster, there is a definitive estimate of the strength of the magnetic field consistent with this range. Such estimates are almost three orders of magnitude higher than hitherto assumed usually. High energy cosmic ray particles can be either focussed or strongly scattered in such magnetic filaments and sheets, depending on the initial transverse momentum. The cosmological background in radio and X-ray wavelengths will have contributions from these intergalactic filaments and sheets, should the magnetic fields really be as high as 0.2 to 2 μgauss

1 Introduction

The observation of the rotation of the plane of polarization as a function of wavelength in extragalactic radio sources has long been known to give unique information on the strength of cosmological magnetic fields (Kronberg 1994). This technique gives information out to redshift of about 2.5, and can in principle do this on the line of sight to a polarized radio source at any redshift.

Information about the strength of cosmological magnetic fields is of key importance for our physical understanding of the early universe. In the standard model for the early phases of the universe there may be a possibility to create magnetic fields, but the data do not require this. It is well known that there is a possibility to create weak magnetic fields form zero by the Biermann battery (Biermann 1950) in a turbulent system with net helicity, such as a rotating star or a shock wave can give. Building on this mechanism several possible origins of the observed magnetic fields can be found; we will discuss two approaches here.

The data situation with respect to cosmic magnetic fields is as follows (Kronberg 1994):

We find neutron stars with magnetic fields of up to about 10^{12} gauss, possibly even more, white dwarfs with fields up to about 10^8 gauss, and normal stars such as the Sun with localized fields up to several 10^3 gauss. The origin of the solar magnetic field is believed to be the lower layers or the lower boundary zone of the hydrogen convection zone on the Sun. This convection zone extends all the way to the surface of the Sun as in all low mass stars, and so the magnetic field can be transported to the photosphere. Interestingly, also massive stars such as OB or WR stars with radiative envelopes show clear evidence of magnetic fields through non-thermal synchrotron emission; the magnetic field may have been transported through circulation currents induced by rotation from the convective core region to the surface.

In the interstellar medium of our Galaxy as well as other galaxies (Beck *et al.* 1996) the magnetic field is of order 10^{-5} gauss, with higher values possible in starburst galaxies such as M82. Even at high redshift already galaxies have their normal magnetic field. This magnetic field appears to be usually in equipartition with the thermal matter in the galaxy, even for short-lived starburst phases of galaxies such as M82. This requires a mechanism to create and/or strengthen the magnetic field which is fast, active over just a few rotation periods of a galaxy.

In clusters of galaxies there is evidence for magnetic fields as well; however, due to the uncertainty of the reversal scale of the field, *i.e.* the scale over which the direction changes sign, the strength of the intra-cluster fields is not clear; it may be a few 10^{-6} gauss or even nearer to 3×10^{-5} gauss, again near equipartition (Enßlin *et al.* 1997).

Outside clusters of galaxies there is one estimate of a magnetic field, again from Kronberg's group (Kim *et al.* 1989), of order 3×10^{-7} gauss, in a filament outside the Coma cluster. We will come back to this measurement below.

Finally, across the universe, one uses the variance of the measured Rotation Measures along the line of sight to many radio quasars at high redshift. The observational Rotation Measure (RM) data of radio quasars limit RM to

$$RM \sim 5 \text{ rad m}^{-2}$$

out to a redshift of $z = 2.5$ (Kronberg & Simard-Normandin 1976; Kronberg 1994 and references therein).

In order to use this measurement, one needs a model for the geometry of the magnetic field. Assuming that the magnetic field is basically homogeneous in a comoving volume, but reverses its direction every length $L_{\text{rev,Mpc}}$ (the reversal scale in Mpc), gives

$$B_{IGM} \lesssim 10^{-9} L_{\text{rev,Mpc}}^{-1/2} \text{ gauss.}$$

If we were to use instead of 1 Mpc for the scaling the bubble scale of the galaxy distribution, then obviously, this upper limit to any magnetic field would be much lower, more like 2×10^{-10} gauss.

In this paper we derive a model for the cosmological geometry of the magnetic field, and then use the data to derive new upper limits for the strength of the magnetic field in the cosmological structures. What we will show is that this exercise leads to an estimate which is about three orders of magnitude higher.

Some of the points described here have been developed in more detail in Biermann, Kang, & Ryu (1997) and Ryu, Kang & Biermann (1997).

We use in the following $h_{0.5}$ as a measure of H_o in units of 50 km/s/Mpc. In section 4, ultra high energy cosmic ray energies are given in EeV $= 10^{18}$ eV.

2 The magnetic field in the cosmos

Our normal understanding of the structure formation in the universe starts with gravitational instabilities, which lead to the formation of Zeldovich pancakes, which in turn intersect with each other and so produce the large scale distribution of galaxies, which we observe. This distribution can be described as a network of irregular soap-bubbles, with filaments arising from the intersection of bubble-walls, and clusters of galaxies at the triple point of intersection. These models then also lead to a steady accretion towards the structures and to shocks around them (*e.g.,* Ryu *et al.* 1993; Kang *et al.* 1994; Ryu & Kang 1997b).

If there was a magnetic field already before the first galaxies formed, then these streaming motions and shocks would strengthen the magnetic field (*e.g.,* Kulsrud & Anderson 1992; Kulsrud *et al.* 1997). If the magnetic field formed with the formation of structure, as suggested by Kulsrud *et al.* (1997), then also todays distribution would strongly correlate with the galaxy distribution. Finally, if the magnetic field formed along with the first galaxies, but form stellar activity, again we would expect the same cosmological inhomogeneity. The consequences of this is what we explore here.

In the following we explore the these two models in some detail.

2.1 Field Generation via Large Scale Structure Formation

In the structure formation of the universe shocks develop along the sheets, filaments and clusters, with strong shearing motions (*e.g.,* Ryu *et al.* 1993; Kang *et al.* 1994; Ryu & Kang 1997b). The shock velocities around clusters reach about

$$v_{acc} \approx 10^8 \, \text{cm/s} \, (\text{M}_{\text{cl}}/\text{R}_{\text{cl}})/(4 \times 10^{14} \text{M}_\odot/\text{Mpc})]^{1/2}$$

for a range of possible densities of the universe of $0.1 \leq \Omega_o \leq 1$ (Ryu & Kang 1997a).

If there was no primordial field, then the Biermann battery mechanism can produce a weak magnetic field in these shocks. This has been followed through numerical simulations in cosmological contexts (Kulsrud *et al.* 1997; Ryu, Kang & Biermann 1997). The turbulent cascade which develops, a Kolmogorov cascade, then pushes the magnetic field energy up in scale to produce a large scale magnetic field in clusters of galaxies (Kulsrud *et al.* 1997). The inverse cascade pushes the magnetic field then up to levels of order 10^{-5} gauss, consistent with observations (Enßlin *et al.* 1997).

This kind of simulations does not have sufficient spatial resolution to follow all the small scale motions in the filaments and sheets, but we conjecture that the field would also be increased. However, the simulations show that the magnetic field, embedded in the fully ionized intergalactic medium, is indeed strongly correlated with the galaxy distribution, and so is expected to be much stronger along filaments and sheets than in the voids.

2.2 Field Generation via Stellar Dynamos and Subsequent Expulsion

The Sun operates a dynamo, changing its magnetic field in polarity every 11 years. This is interpreted as the consequence of a dynamo, which is now believed to operate at the lower boundary zone of the hydrogen convection layer. Other stars clearly can also produce magnetic fields, and so the observation of ubiquitous magnetic fields on stars can be understood. The

massive stars also have evidence for magnetic fields as seen through non-thermal radio emission (Abbot *et al.* 1986; Bieging *et al.* 1989). Massive stars explode as supernovae, then spilling their magnetic field into the interstellar medium. The most massive stars already pollute the interstellar medium with their magnetic field through their powerful winds. These winds have been argued to contain magnetic fields up to a an order of magnitude of 3×10^3 gauss on the surface of the star (Maheswaran & Cassinelli 1992). Then these winds may actually have some additional momentum due to their magnetic fields (Seemann & Biermann 1997).

If the moderate estimates for the strength for these magnetic fields in stellar winds (Biermann & Cassinelli 1993) can be confirmed, then the winds terminate in the interstellar medium with a remaining field of order 10^{-5} gauss (after allowing for a factor of 4 from the shock transition). This means that the magnetic field injected into the interstellar medium is already near equipartition from the injection region, which changes the requirements for a successful dynamo theory drastically. The dynamo process no longer has to strengthen the field, but it has to order it starting from near equipartition. Such ordering has been found in simulations (A. Shukurov, personal communication through R. Beck to P.L. Biermann), and so this would enable the dynamo process to operate on a few rotation periods, rather than very many rotation periods, which are not available for a galaxy.

This mechanism would also allow to explain why starburst galaxies have such a strong magnetic field, but again in equipartition with the thermal energy density of the matter (Kronberg *et al.* 1985), despite the fact that a typical starburst cannot be very old, at most 10^8 years.

A similar argument can be made for the battery mechanism and the dynamo operating in compact accretion disk, be it around protostars, white dwarfs, neutron stars, or black holes. Especially the black holes now believed to lurk in every early Hubble type galaxy are often observed to eject jets that power gigantic radio lobes. These jets and lobes are filled with a magnetic field, as testified once again by the non-thermal synchrotron radio emission.

3 Application of the models

In the simulation we used to estimate the magnetic field strength in filaments and sheets, a standard cold dark matter (CDM) model was adopted with $\Omega_b = 0.06$, $h = 0.5$, and a bias parameter of $\sigma_8 = 1.05$ (see Kulsrud *et al.* 1997; Ryu, Kang & Biermann 1997). With a large number of randomly selected straight lines through a simulation we then calculated the Rotation Measure through such a simulated universe, and its variance to a source at redshift $z = 2.5$. Care was taken to avoid clusters of galaxies, because we do not propose to discuss their magnetic field here; however, it follows already that the fairly high magnetic fields advocated by Enßlin *et al.* (1997) are consistent with the simulations. Comparing the variance of the Rotation Measure in the simulations with the observed upper limit we then obtain an upper limit of the magnetic field strength in filaments and sheets.

Depending on the various cosmology models, we have a range of possible upper limits B_u. At the observed upper limit of the Rotation Measure we so find

$$0.2 \, \mu\text{gauss} \; h_{0.5}^{-2} \; < \; B_u \; < \; 2 \, \mu\text{gauss} \; h_{0.5}^{-2} \; .$$

It is then interesting to come back to the one case where a definite estimate for an extra-cluster magnetic field has been made, by Kim *et al.* (1989). They find magnetic fields in the plane of the Coma/A1367 supercluster of 0.3 to 0.6 μgauss, which is already in the range, but still consistent with our upper limits.

4 Conclusion and Discussion

In conclusion, our result indicates that the present limit set by RM observations allows for the existence of magnetic fields of up to ~ 1 μgauss in filaments and sheets, if the magnetic field in the voids is much smaller. Such a geometry of the universal magnetic field is expected by simulations of structure formation. We shall discuss some consequences of this result:

4.1 Equipartition fields and cosmological background radiation

We may compare the above upper limit with the strength of the magnetic field whose energy is in equipartition with the thermal energy of the gas in filaments and sheets. The equipartition magnetic field strength can be written as,

$$B \;=\; 0.17\,h_{0.5}\,\sqrt{\frac{T}{3\times 10^6\,\mathrm{K}}\,\frac{\rho_b}{0.3\,\rho_c}}\;\mu\,\mathrm{gauss}$$

(Ryu, Kang, & Biermann 1997). The fiducial values $T = 3\times 10^6\,\mathrm{K}$ and $\rho_b = 0.3\,\rho_c$ may be appropriate for filaments (see, Kang *et al.* 1994), but may be somewhat too large for sheets. So, the predicted equipartition field strength in filaments is $\sim 0.3\,\mu$gauss, and maybe $\lesssim 0.1\,\mu$gauss in sheets, which is close to, but several times smaller than the overall limit set by RM observations.

Filaments and sheets can contribute radiation at X-ray wavelengths to the cosmological background. Using fiducial values and a typical size of $20h_{0.5}^{-1}\mathrm{Mpc}$, the luminosity of filaments and sheets in the soft X-ray band $(0.5-2\,\mathrm{keV})$ is expected to be $\lesssim 3\times 10^{41}\,\mathrm{erg\,s^{-1}}$. Actually, Miyaji *et al.* (1996) and Soltan *et al.* (1996) reported the detection of extended X-ray emission from structures of a comparable size and a luminosity of $\approx 2.5\times 10^{43}\,\mathrm{erg\,s^{-1}}$, which is correlated to Abell clusters, suggesting that the temperature and gas density outside clusters could even be considerably larger than the fiducial values assumed above. In any case, if this observation can be further confirmed, and equipartition of magnetic field and gas density is assumed, it would imply the existence of a $\sim 1\,\mu$gauss magnetic field on large scales *outside* galaxy clusters, and thus be an impressive confirmation of our results.

Another interesting exploration is the synchrotron radio emission arising from filaments and sheets of a magnetic field of order $0.1-1$ μgauss. We noted that the original estimate of the magnetic field in the plane of the Coma/Abell 1367 supercluster was based on a synchrotron radio continuum measurement (Kim *et al.* 1989). Since our RM upper limits for the magnetic field refer to a gross average of filaments and sheets in the universe, the comparison to just a single observation is likely to be affected by selection effects. If such estimates could be made for a statistically complete sample of locations outside big clusters, this would constitute another definite test of the underlying concept in the simulations described above, including the strength of the magnetic field more directly than X-ray observations. Since this project would involve observations at low radio frequencies, it would be ideal for the new capabilities coming on line at the GMRT (Giant Meterwave Radio Telescope) in India and at the VLA in the USA.

Whether filaments and sheets can contribute radiation at other wavelengths, such as γ-ray energies, to the cosmological background remains an unanswered but challenging question at this time.

4.2 Origin of ultra high energy cosmic rays

The discoveries of several reliable events of high energy cosmic rays at an energy above $100\,\mathrm{EeV}$ raise questions about their origin and path in the universe, since their interaction with the cosmic microwave background radiation (MBR) limits the distances to their sources to less than 100 Mpc, perhaps within our Local Supercluster.

The large-scale accretion shocks in reagions where a seed magnetic field can be generated are probably the biggest shocks in the universe, with a typical size in the range of 1-10 Mpc and very strong with a typical accretion velocity $\gtrsim 1000\,\mathrm{km\,s^{-1}}$. With up to $\sim 1\,\mu$gauss magnetic field around them, they could serve as possible sites for the acceleration of high energy cosmic rays by the first-order Fermi process (Kang, Ryu & Jones 1996). With the particle diffusion model in quasi-perpendicular shocks (Jokipii 1987), the observed cosmic ray spectrum between 10 and 100 EeV could be explained with reasonable parameters if about 10^{-4} of the infalling kinetic energy can be injected into the intergalactic space as energetic particles; for the more conservative assumption of Bohm diffusion, however, no considerable contribution above 10 EeV is expected (Kang, Rachen & Biermann 1997).

It has been speculated whether the shocks on larger scales, like expected around filaments and sheets, could make a significant contribution as well (Norman, Melrose & Achterberg 1995); a closer look shows, however, that due to Bethe-Heitler losses at the microwave background this can work out only up to ~ 30 EeV, and only if quasi-perpendicular shocks are assumed. However, the simulations suggest that the latter assumption may apply, and even though filaments and sheets are still not expected to be efficient accelerators of the highest energy cosmic rays, the special shock geometry present around them can have a severe impact on their propagation, as discussed below.

4.3   Propagation of ultrahigh energy cosmic rays

The Haverah Park and Akeno data indicate that the arrival directions of the ultra high energy cosmic ray particles are in some degree correlated with the direction of the Supergalactic Plane (SGP; Stanev *et al.* 1995; Hayashida *et al.* 1996; Uchihori *et al.* 1997). It was pointed out by Waxman *et al.* (1997), that this correlation appears to be better than the correlation of any reasonable source population to this sheet.

This apparent contradiction is removed by the assumption of a magnetic field $\lesssim 0.1\,\mu$gauss aligned with the SGP. It is easy to show that cosmic rays are confined in the sheet if $E < eB_{\mathrm{sh}}H_{sh} \sim 700$ EeV for the fiducial values used above and a sheet thickness of $5/h_{0.5}$ Mpc; thus confinement is possible up to the highest observed cosmic ray energies without exhausting the limits allowed in our model. This involves essentially two effects which together pronounce the supergalactic plane in the cosmic ray arrival direction distribution: (a) Due to the accretion flows infalling toward the supergalactic plane, the high energy cosmic can be focussed in the direction perpendicular to the SGP, analogously but in the opposite direction to solar wind modulation. This "focussing" means that particles with a sufficiently small transverse initial momentum would slowly decrease their transverse momentum even more by interaction with the incoming accretion flow; this then produces transverse trapping. This effect would be most efficient for those particles with a sufficiently small initial momentum transverse to the sheet (Biermann, Kang & Ryu 1997). However, the details of this effect depend on the magnetic field configuration and need further consideration. (b) Since the particles are captured inside the sheets, the dilution with distance d is $1/d$ instead of $1/d^2$, increasing the cosmic ray flux from any source within the direction of the SGP appreciably compared to the three-dimensional dilution expected for other sources. So we may see sources in the SGP to much larger distances than expected so far. On the other hand, most particles, *i.e.* those with a large initial transverse momentum, would be strongly scattered at the magnetic field, obliterating all source information from their arrival direction at Earth, consistent with the data (Uchihori *et al.* 1997, Waxman *et al.* 1997).

Another effect influences the modification of the cosmic ray spectrum at the highest observed energies, where interactions with the MBR limit the propagation distance to $\lesssim 100$ Mpc. Here, the presence of shock waves around the filaments and sheets leads to a truly universal particle

acceleration, competing with the energy losses. Since the particles never effectively leave the acceleration region, the advection losses present in normal shock acceleration scenarios are replaced by the energy losses in the MBR, leading to a stationary spectrum comparable with a E^{-3} spectrum, if the acceleration timescale is larger than the loss time scale by about a factor of 4 (Rachen 1997). Superposed with a flat injection spectrum of point sources (like radio galaxies of clusters of galaxies), we can expect that the cosmic ray spectrum can continue with the observed slope up to more than $300\,\mathrm{EeV}$, even if the closest source is more (but not much more) distant than $\sim 100\,\mathrm{Mpc}$. Also here, more detailed calculations are required to discern the real limits, but it is already clear that most results obtained for the extragalactic transport of cosmic rays, which were obtained without regarding the large scale structure, have to be reconsidered.

Acknowledgments

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